Development of YAG:Dy Thermographic Phosphor Coatings for Turbine Engine Applications

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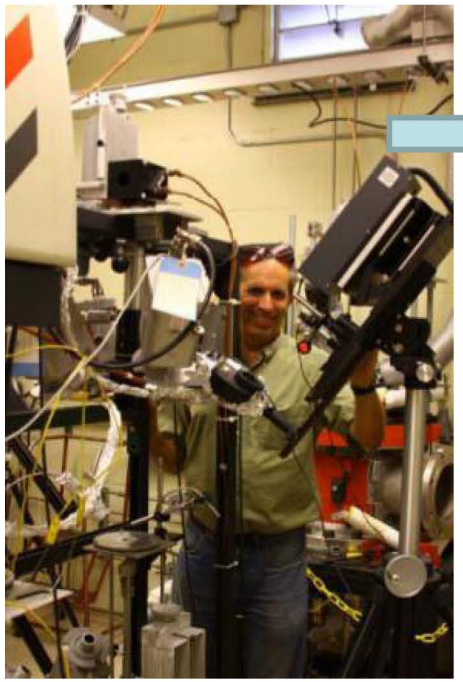
AFRL Versatile Affordable Advanced Turbine Engines (VAATE) Project

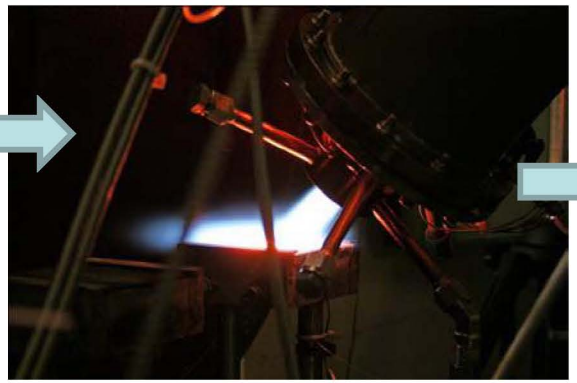
Gas Turbine Engine Sensor and Instrumentation Development

Project 1: TBC Health & Component Temperatures of Turbine Blades & Vanes



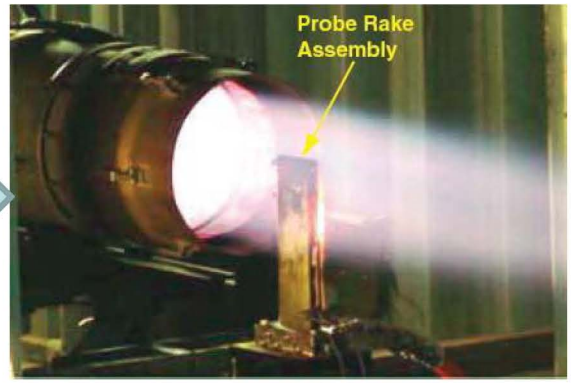
NASA GRC High-Heat-Flux Laser Facility
•Proof-of-concept with easy optical access, no radiative background, no probe heating issues.

Demonstrated to 1360ºC. ✓



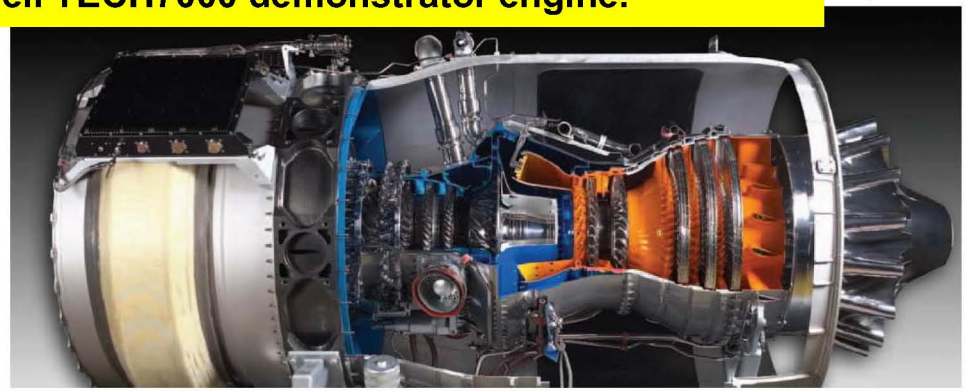
Williams International Combustor Burner Rig
•Address probe/TP survivability & ability to "see" through flame.

Demonstrated to >1400ºC. ✓



AEDC J85-GE-5
•Probe/translate through afterburner flame.
•Opportunity to test excitation/collection integrated probe.

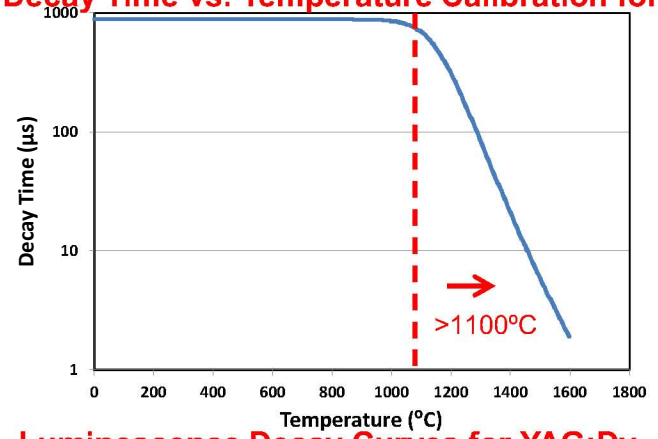
Goal: Demonstrate thermographic phosphor (TP) based temperature measurements to 1300ºC on TP/TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.



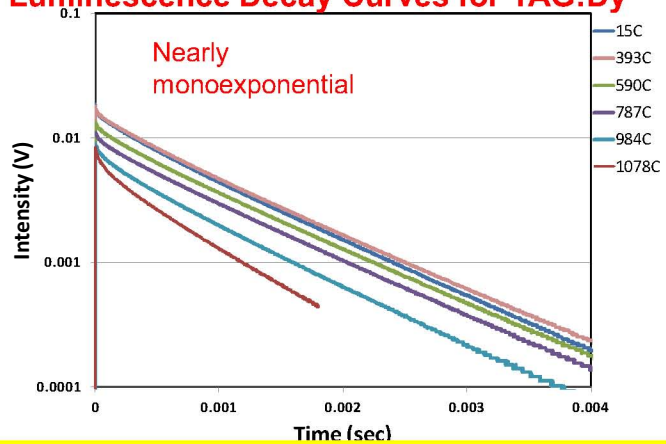
Basis for Selection of YAG:Dy

- Advantages of YAG:Dy (at least in powder form produced at high temperature)
  1. Excellent temperature sensitivity from 1100º to 1700ºC.
  2. Higher upper temperature limit than other thermographic phosphors.
  3. Short-wavelength emission at 456 nm reduces interference from background thermal radiation.
  4. Nearly single exponential decay for simple, robust decay time determination.

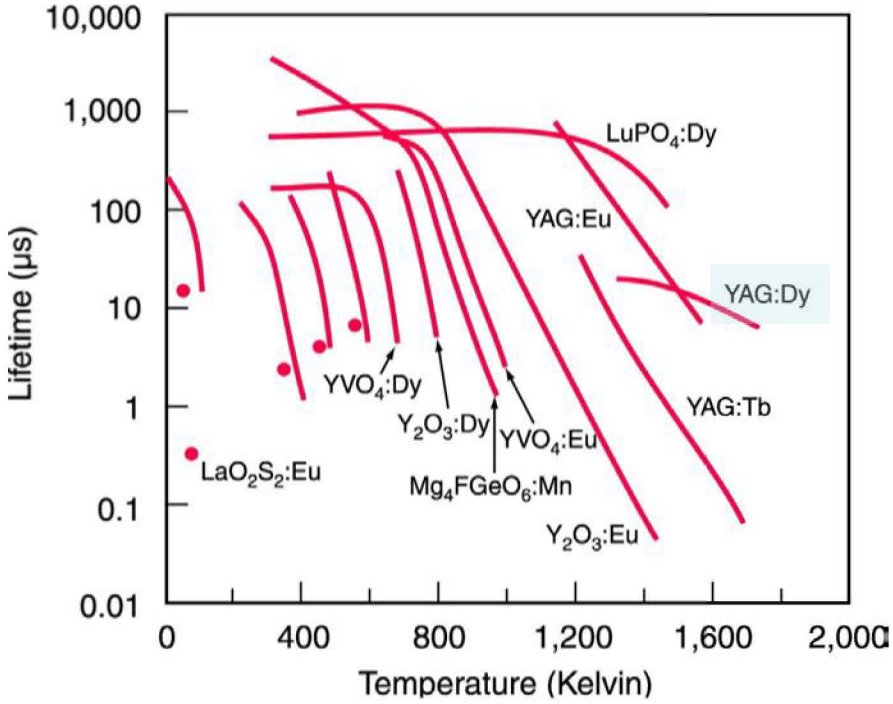
Decay Time vs. Temperature Calibration for YAG:Dy



Luminescence Decay Curves for YAG:Dy



Decay Time vs. Temperature



But, will YAG:Dy coatings exhibit these desirable attributes because temperatures of coating processing restricted to much lower temperatures (<1200ºC) than powder processing?

Coating Deposition Methods Investigated

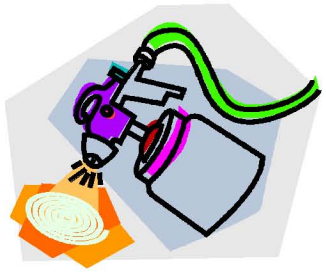
- Binder-Based Paint Application
  1. Mixture of YAG:Dy powder and ZAP binder (ZYP Coatings, Oak Ridge, TN)
  2. Air-brush or paint brush application.
  3. Fire to produce coating consisiting of YAG:Dy powder particles in $AlPO_4$ matrix.
  - Simple, fast, & inexpensive.
  - Incorporates fully crystallized phosphor powder.

- Electron-Beam Physical Vapor Deposition (EB-PVD)
  - E-beam evaporation of YAG:Dy ingot at Penn State.
  - Most compatible for in-line industrial thermal barrier coating (TBC) deposition.
  - Excellent thickness control.
  - Desirable microstructure.

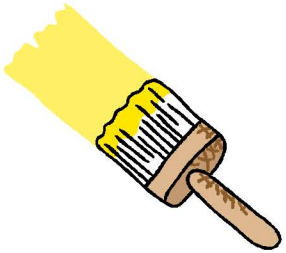
- Solution Precursor Plasma-Spray (SPPS)
  - Injection of atomized solution into plasma jet.
  - Low-cost alternative to EB-PVD and conventional plasma-spray.
  - Easily tailorable composition.

Binder-Based Paint Application
ZAP YAG:Dy

ZAP YAG:Dy on Plasma-Sprayed YSZ

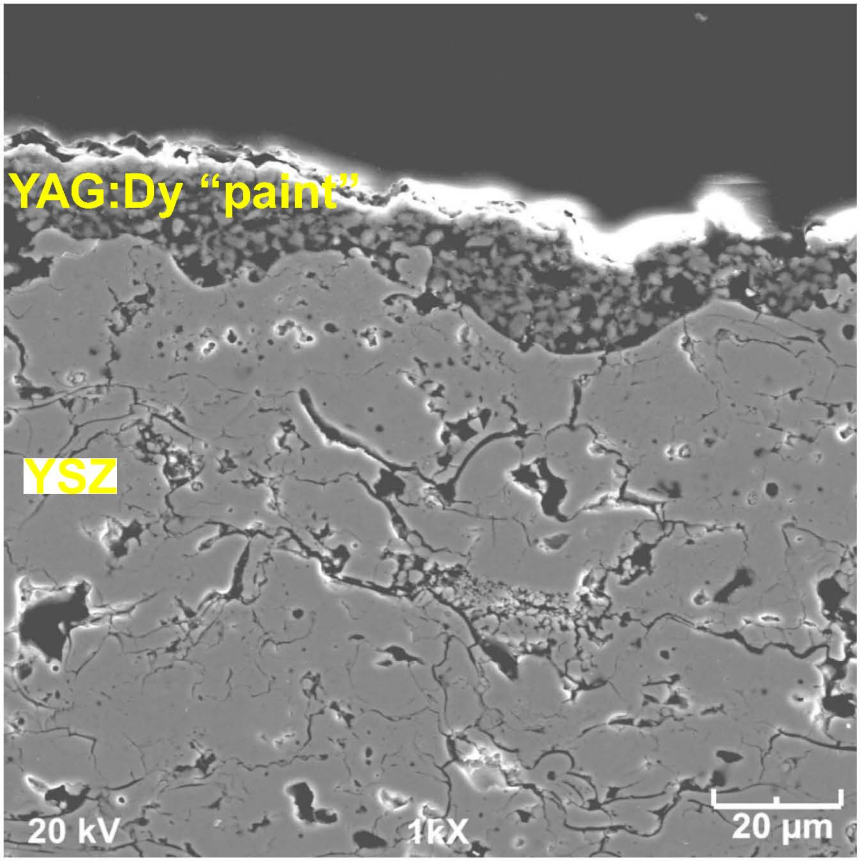


or



+

3hr @1000ºC

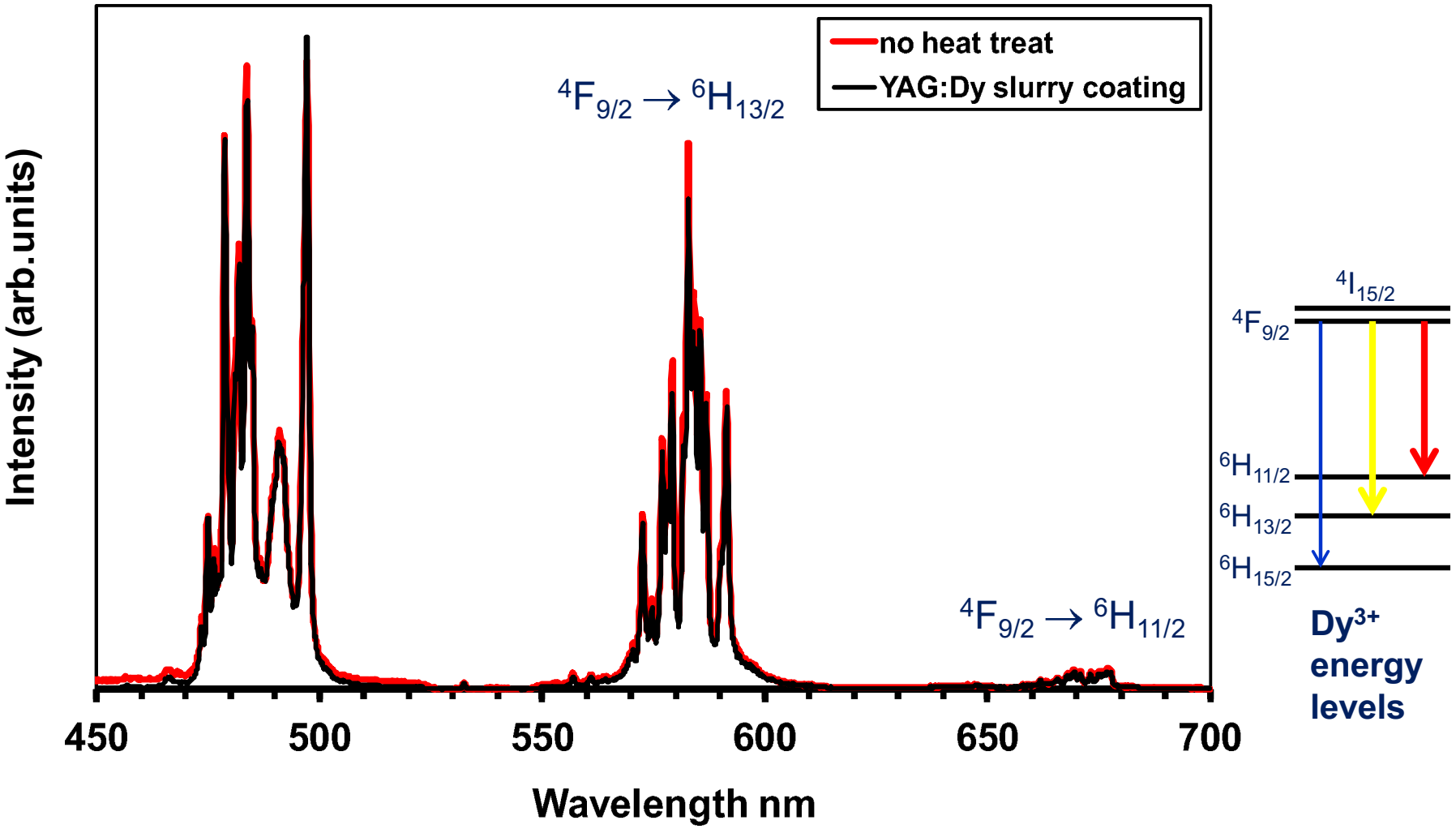


Coating consists of YAG:Dy powder particles in aluminum phosphate matrix.

Effect of Heat Treatment on ZAP YAG:Dy

Time-Averaged Luminescence Emission

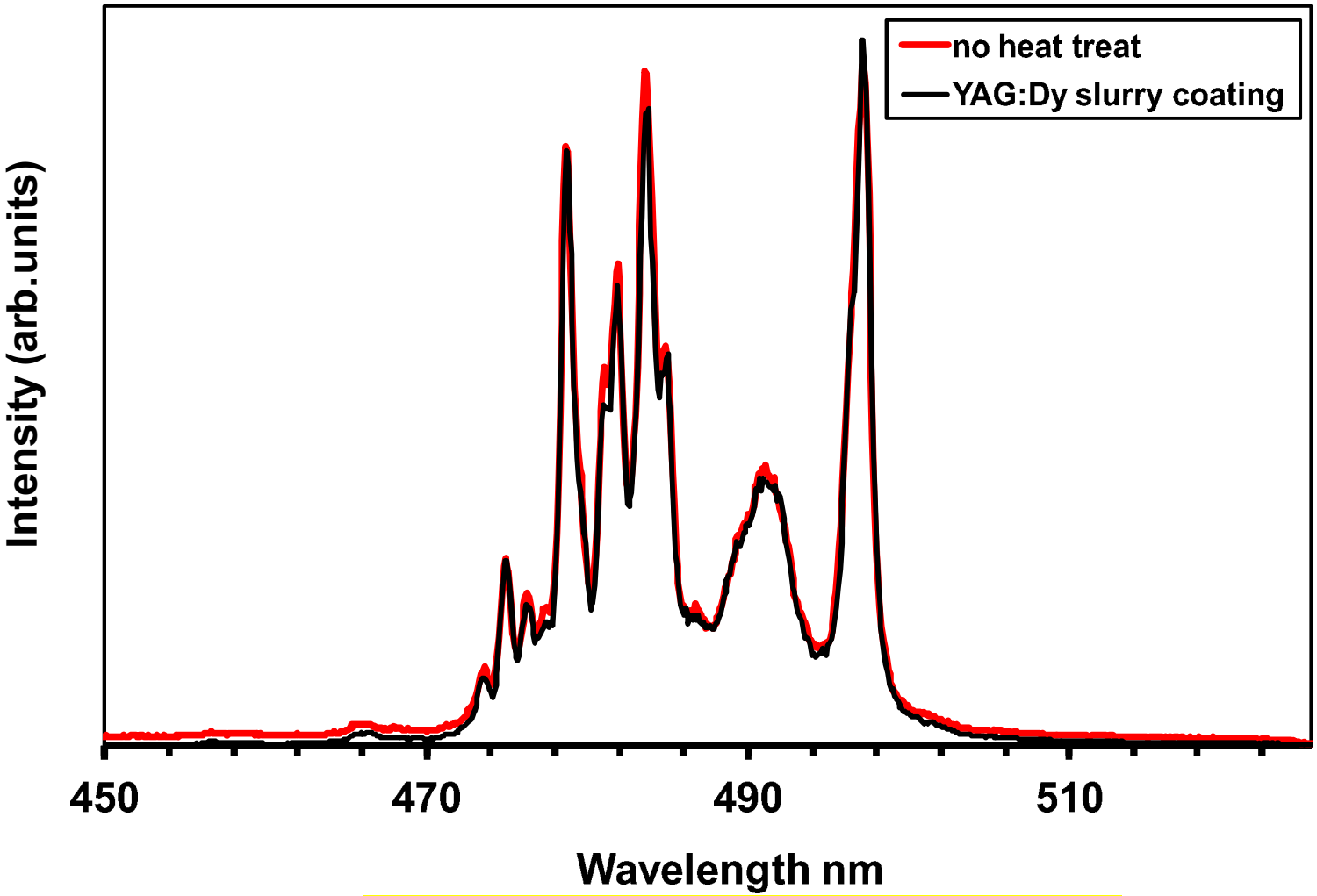
$^4F_{9/2} \rightarrow {}^6H_{15/2}$ Excitation at 355 nm



ZAP YAG:Dy coating exhibits desired YAG:Dy emission spectrum.

Effect of Heat Treatment on ZAP YAG:Dy

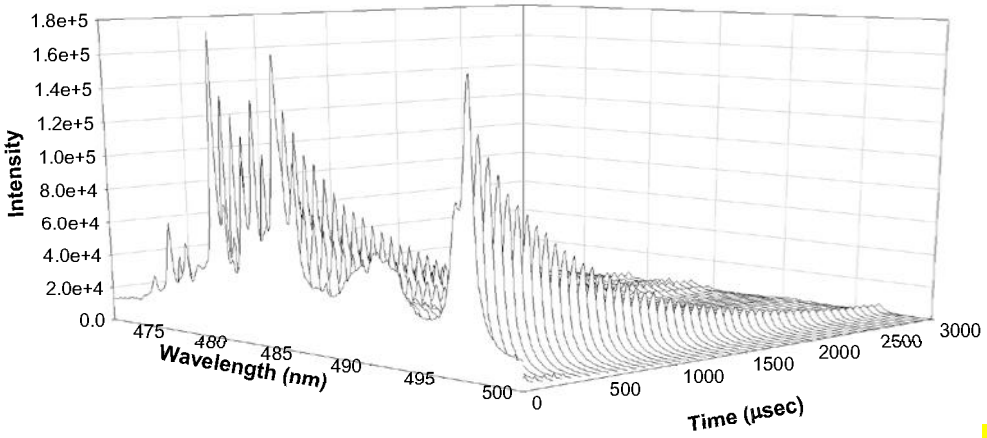
Time-Averaged Luminescence Emission
Excitation at 355 nm



Both slurry coating and ZAP YAG:Dy coating exhibit desired YAG:Dy emission spectra.

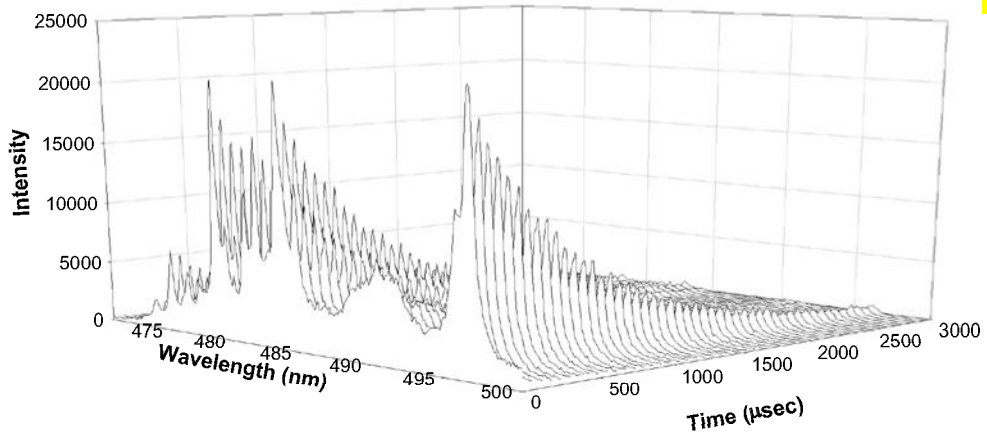
Time-Resolved Luminescence
15ºC

ZAP YAG:Dy no heat treatment



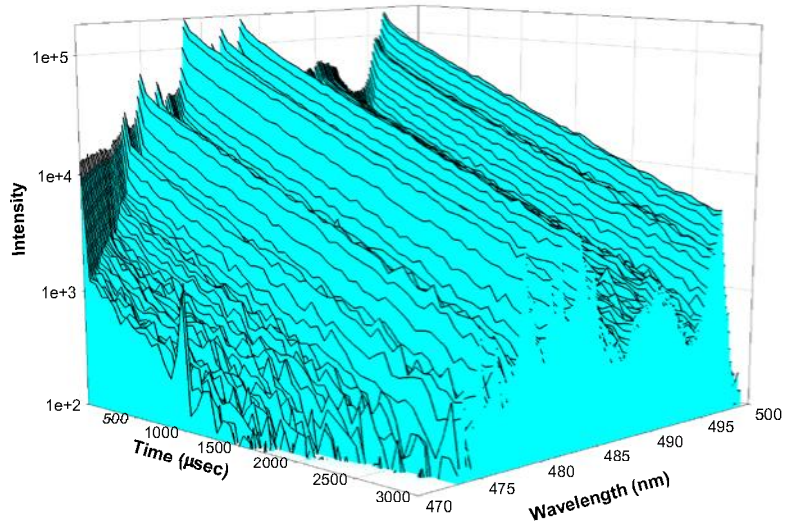
ZAP YAG:Dy emission spectrum + decay appear identical to that of YAG:Dy powder standard. *Very promising.*

YAG:Dy Powder Standard

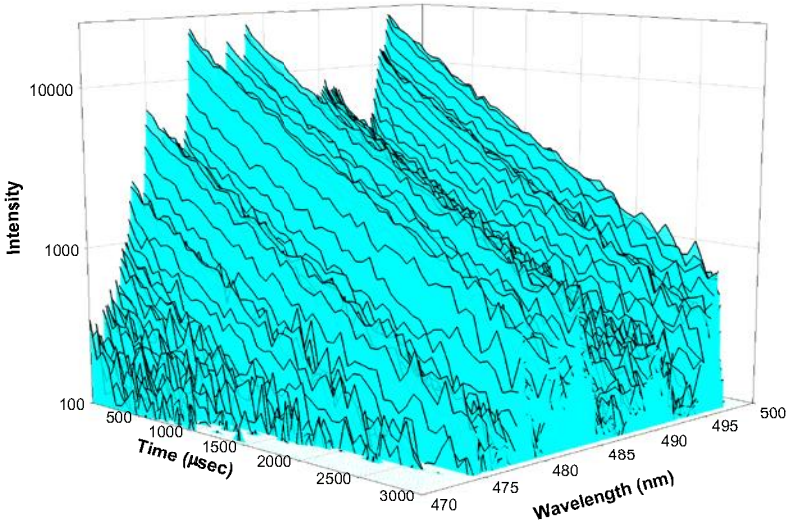


Time-Resolved Luminescence with Logarithmic Intensity Scale 15ºC

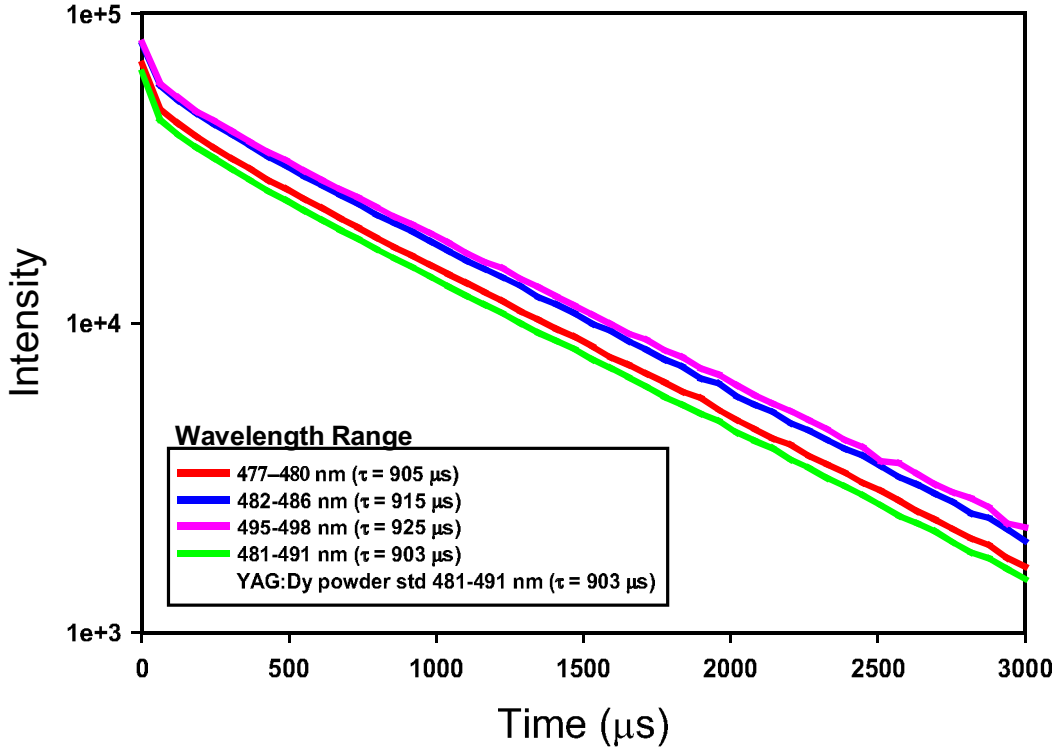
ZAP YAG:Dy no heat treatment



YAG:Dy powder standard



ZAP YAG:Dy No Heat Treatment Luminescence Decay Curves at 15ºC Compared to YAG:Dy Standard

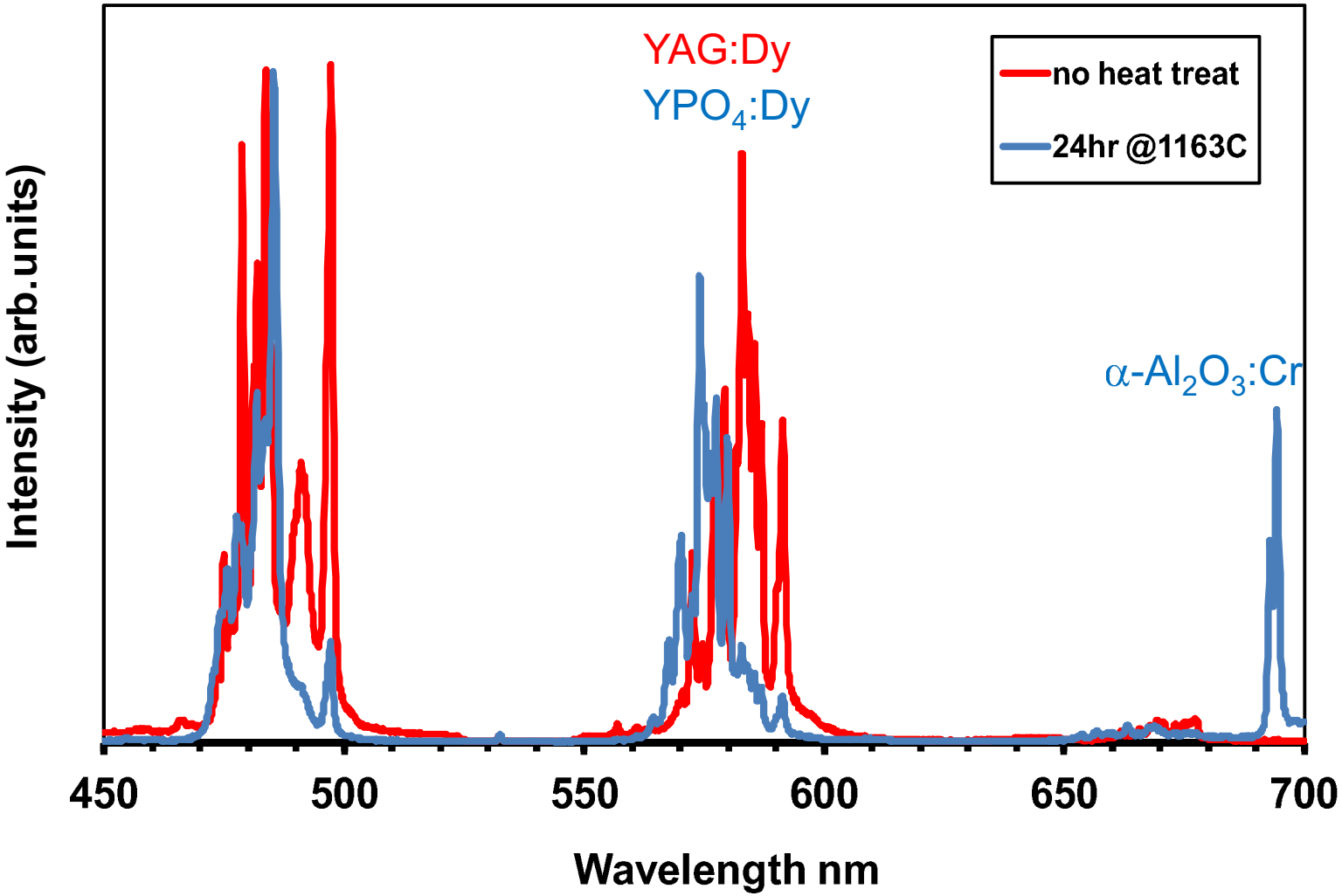


- **Nearly single exponential decay.**
- **Uniform decay rate over full wavelength range.**

Effect of Heat Treatment on ZAP YAG:Dy

YAG:Dy
YPO_4:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

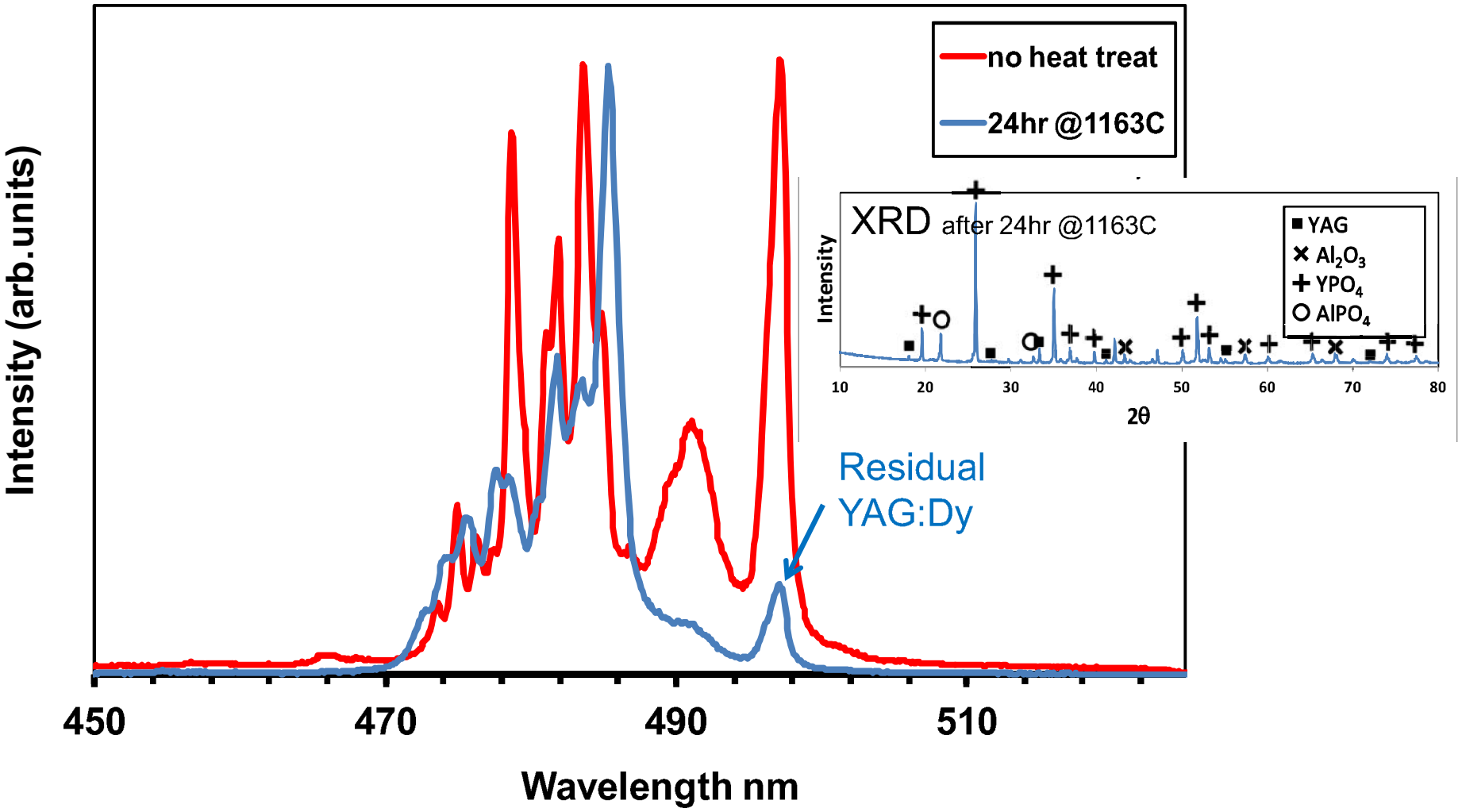


Proposed reaction: $Y_3Al_5O_{12} + 3AlPO_4 \rightarrow 3YPO_4 + \alpha\text{-}Al_2O_3$

YAG binder

Effect of Heat Treatment on ZAP YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

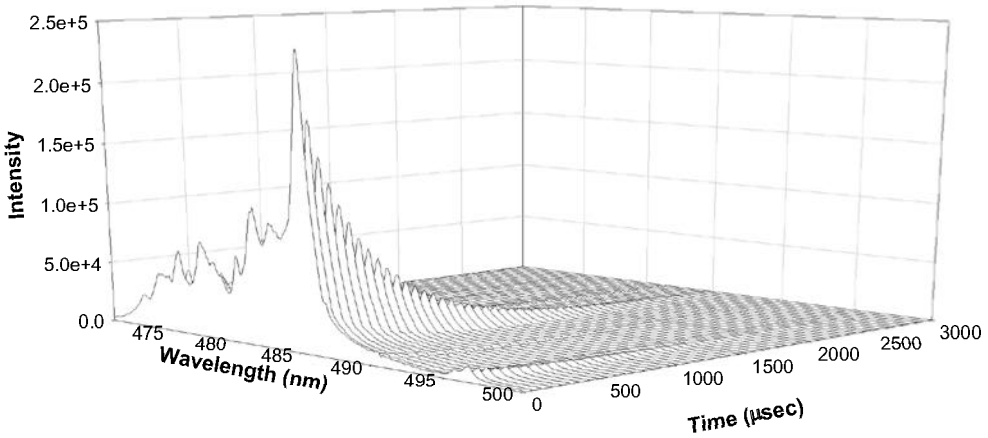


Proposed reaction: $Y_3Al_5O_{12} + 3AlPO_4 \rightarrow 3YPO_4 + \alpha\text{-}Al_2O_3$

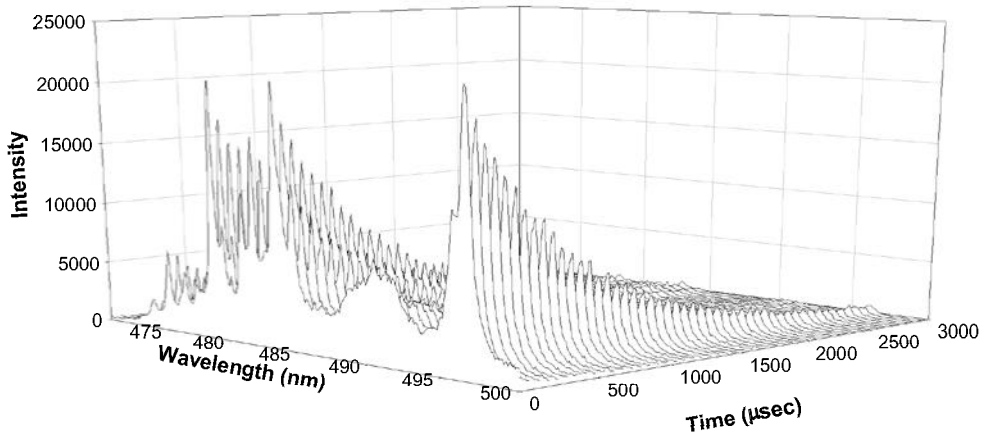
YAG binder

Time-Resolved Luminescence
15ºC

ZAP YAG:Dy 24hr @1163ºC



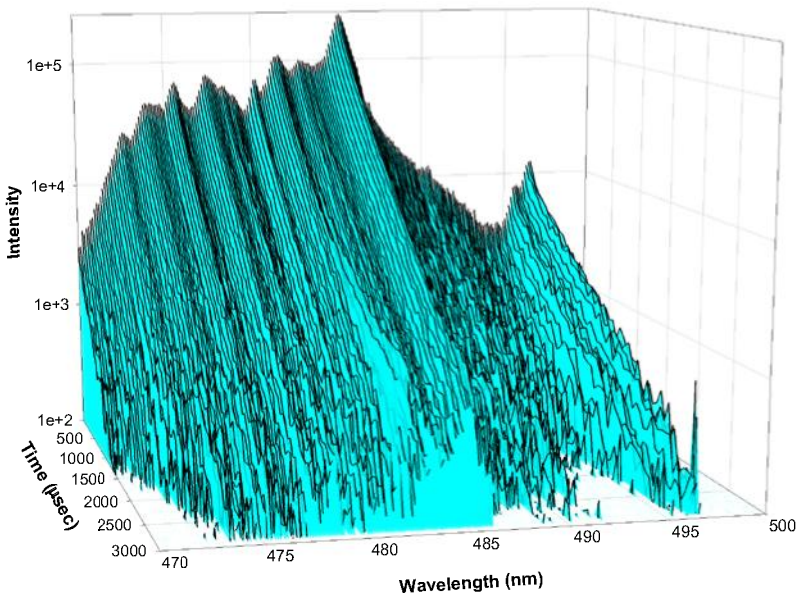
YAG:Dy Powder Standard



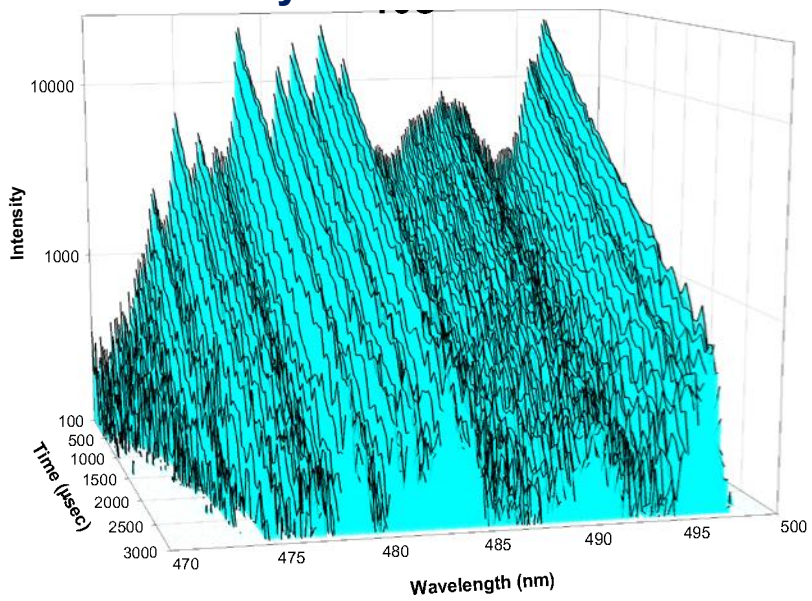
After 24hr @1163ºC, ZAP YAG:Dy emission spectrum is completely different and exhibits faster decay than YAG:Dy powder standard. *Not so promising.*

Time-Resolved Luminescence with Logarithmic Intensity Scale 15ºC

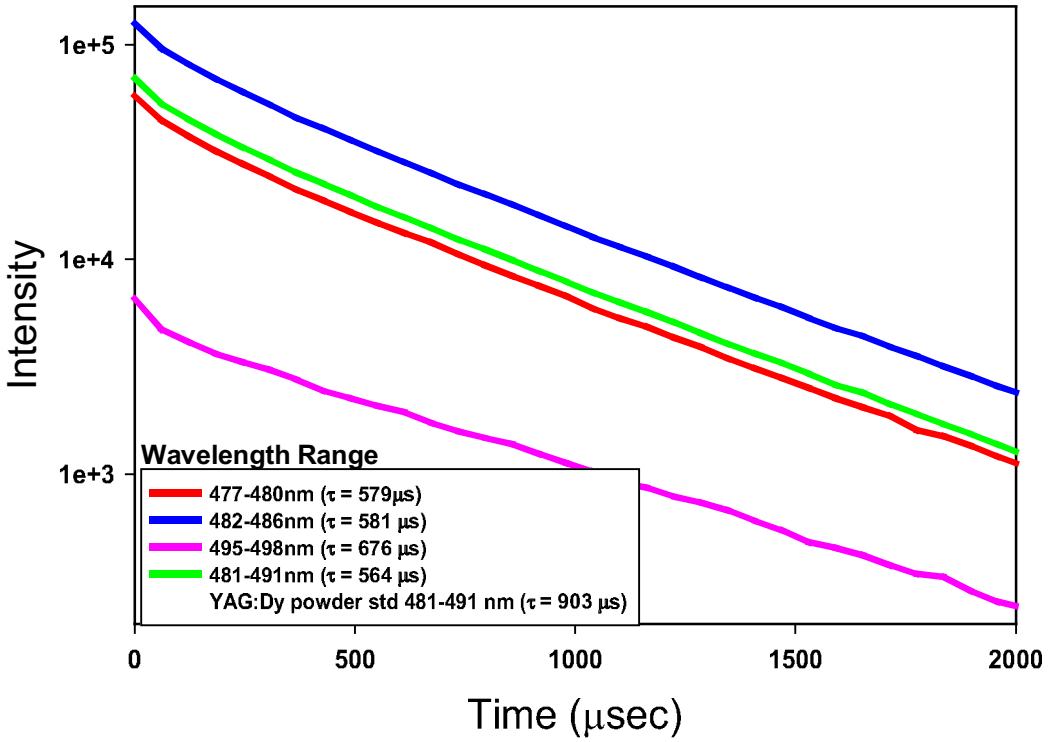
ZAP YAG:Dy 24hr @1163ºC



YAG:Dy Powder Standard



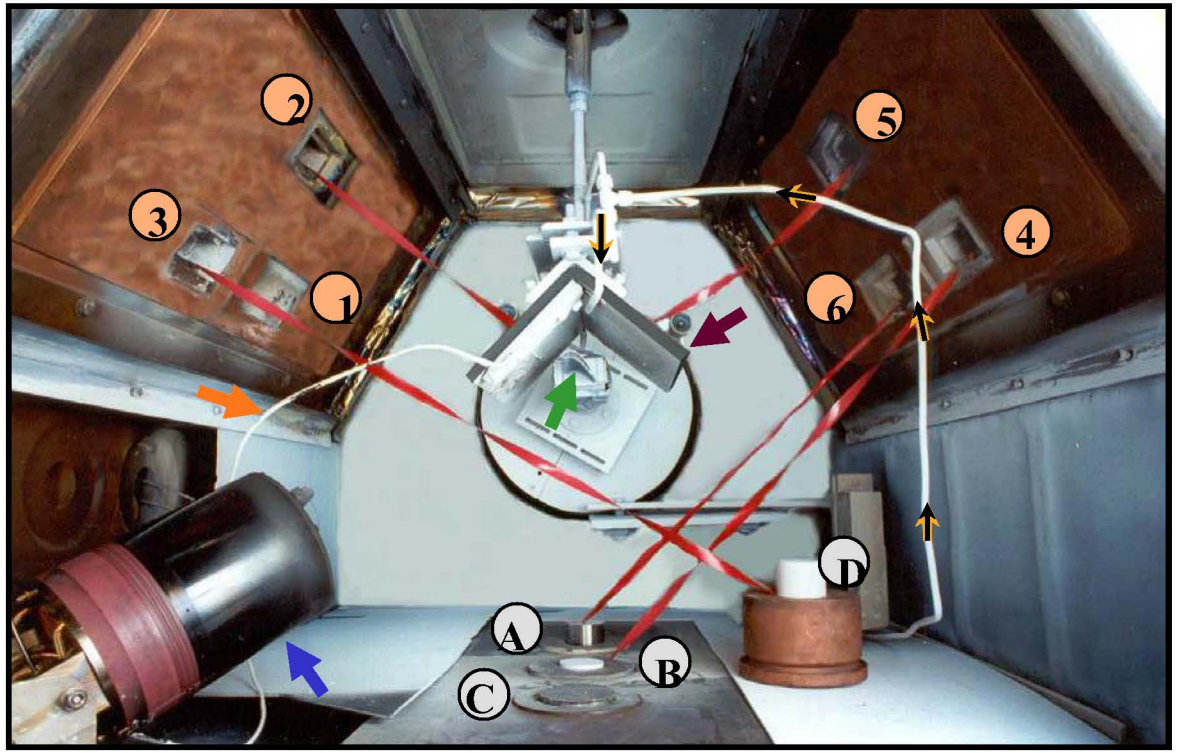
ZAP YAG:Dy 24hr @1163C Luminescence Decay Curves at 15ºC Compared to YAG:Dy Standard

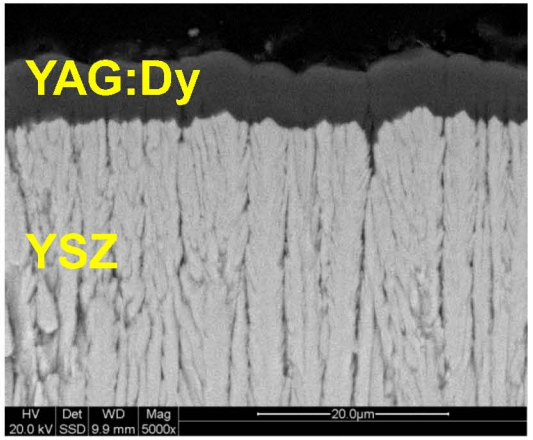


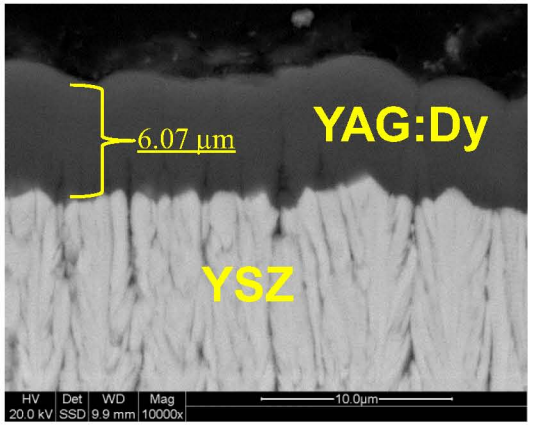
- Steeper decay than YAG:Dy standard.
- Spectra contain mixture of YPO4:Dy & unreacted YAG:Dy. Peak at 496nm mostly from unreacted YAG:Dy.
- ZAP coating unsuitable for high temperature measurements for any significant duration.

EB-PVD YAG:Dy

Multi-Ingot EB-PVD Chamber at Penn State







1-6 Guns

A-D Crucibles + Ingots

Oxygen Supply Path

Thermocouple

Airfoil

Ion Source

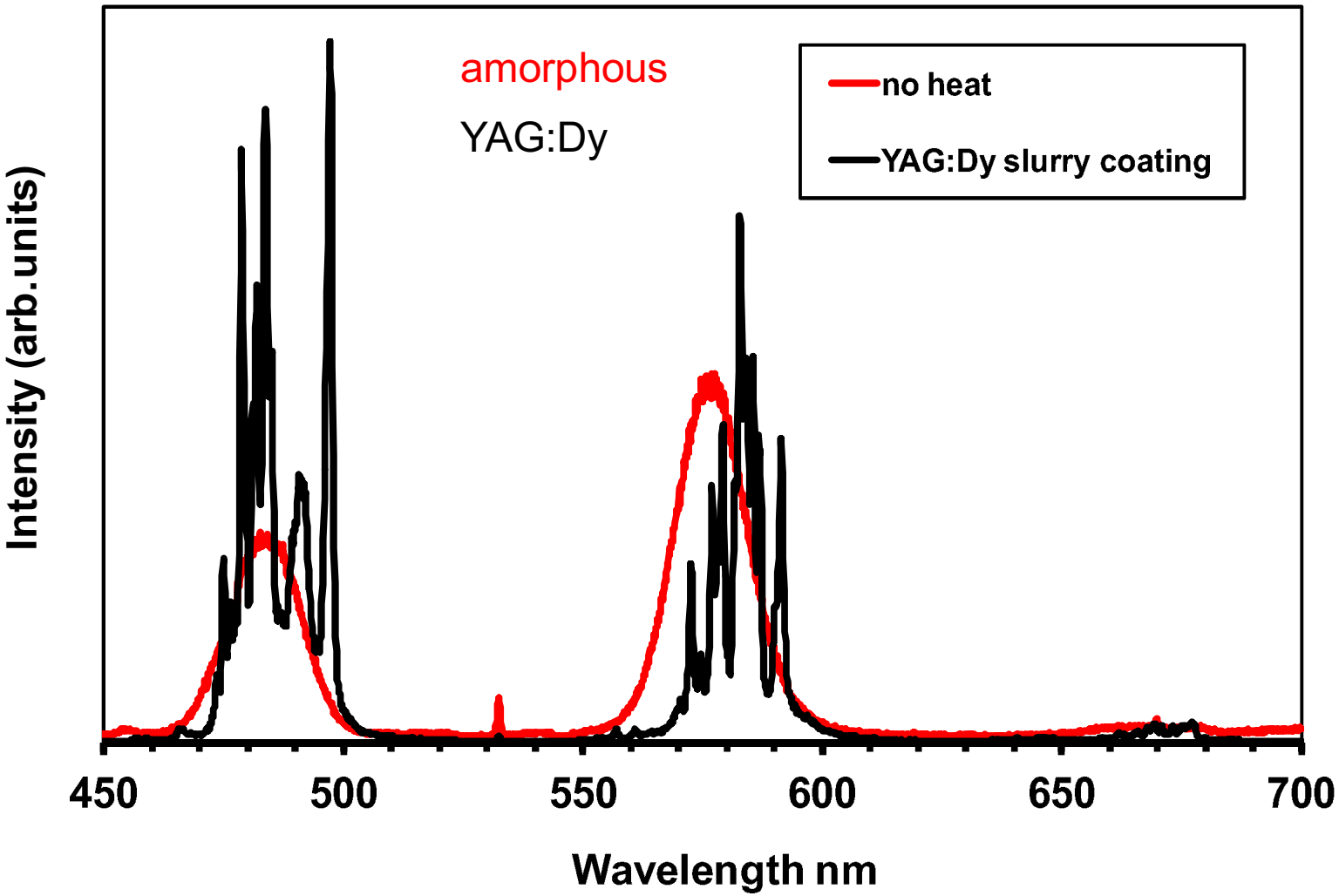
Graphite heating plate

Ingots (Trans-Tech):

- Undoped 7YSZ
- YAG:Dy

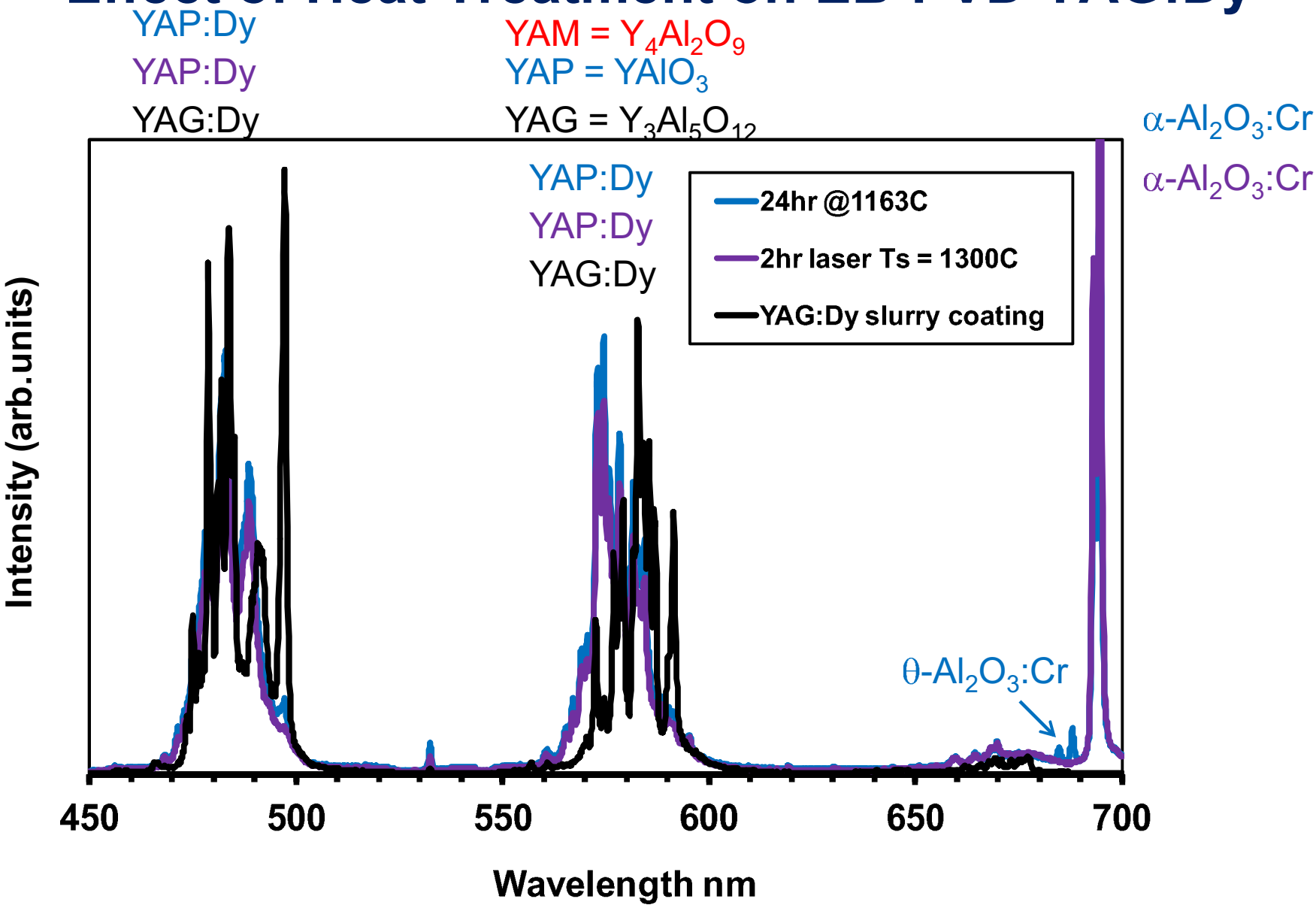
Effect of Heat Treatment on EB-PVD YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm



Peak positions & ratios indicate amorphous phase is not precursor to YAG.

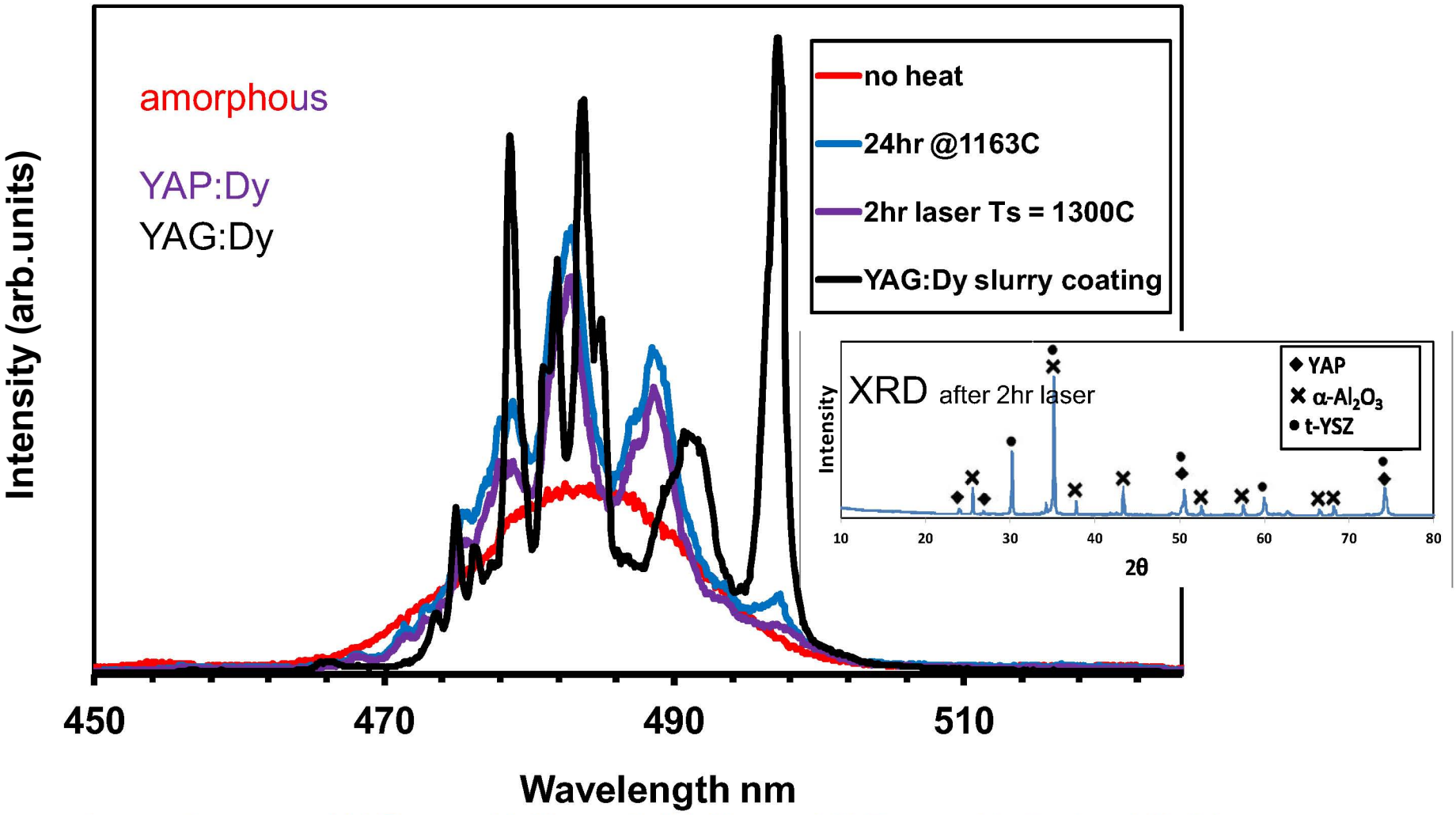
Effect of Heat Treatment on EB-PVD YAG:Dy



Amorphous $\rightarrow$ YAP + α-Al_2O_3 + θ-Al_2O_3 $\rightarrow$ YAP + α-Al_2O_3 (no YAG)

Effect of Heat Treatment on EB-PVD YAG:Dy

Time-Averaged Luminescence Emission
Excitation at 355 nm

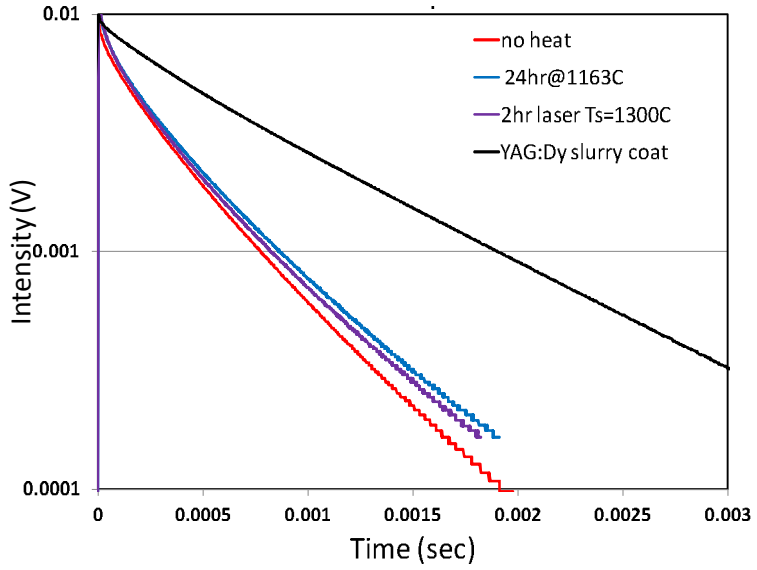


Amorphous → YAP + α-Al_2O_3 + θ-Al_2O_3 → YAP + α-Al_2O_3 (no YAG)

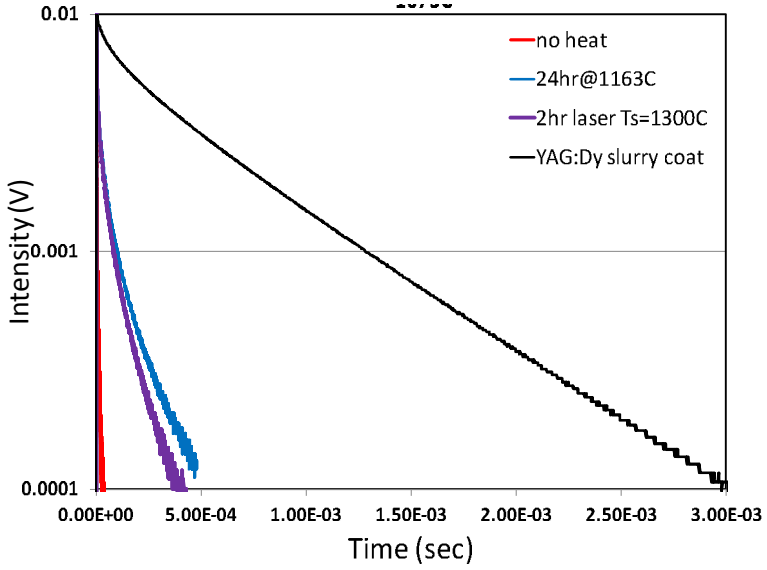
YAG is difficult to achieve due to non-congruent evaporation from ingot.

Effect of Heat Treatment on Decay Curves for EB-PVD YAG:Dy

Luminescence Decay at Room Temperature



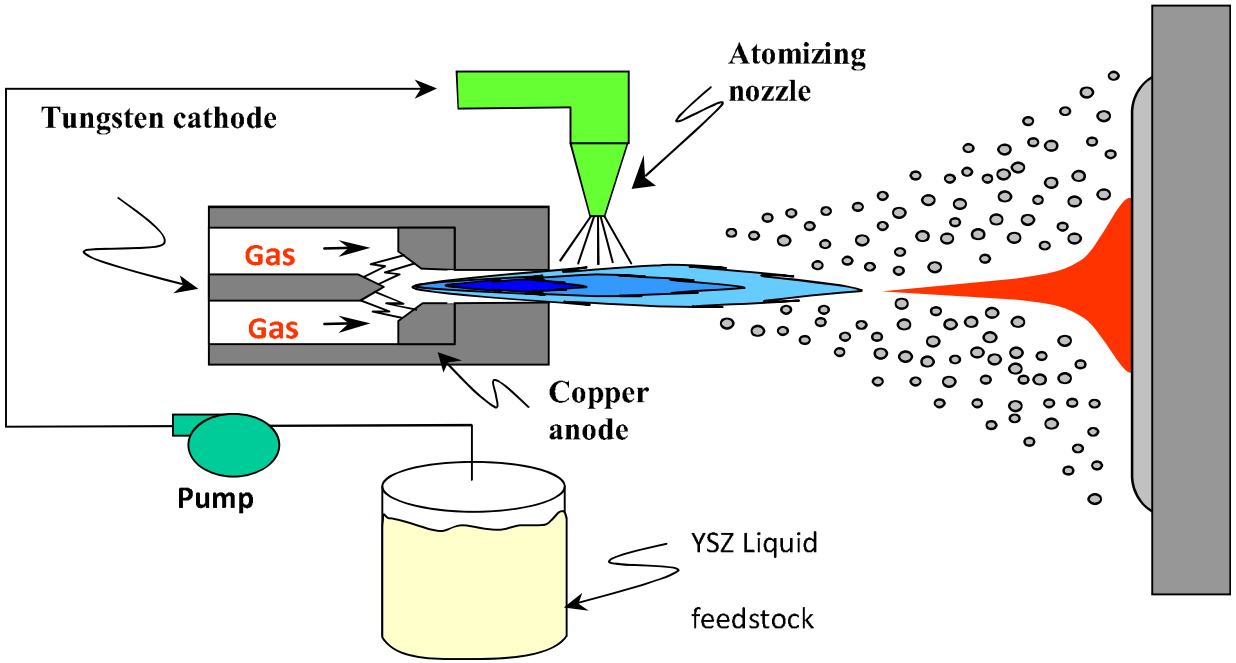
Luminescence Decay at 1075ºC

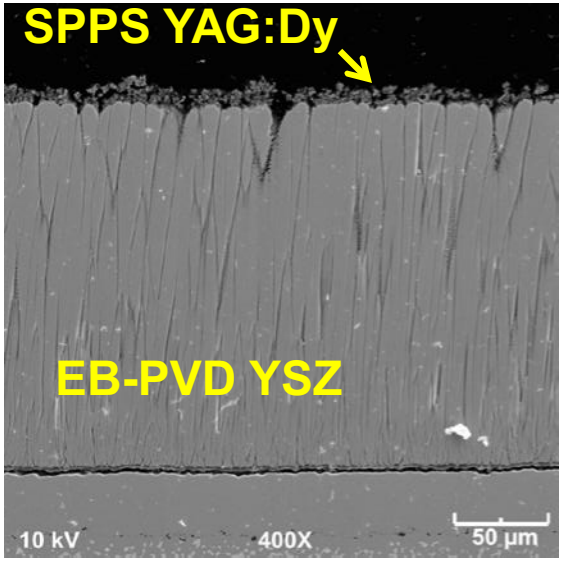


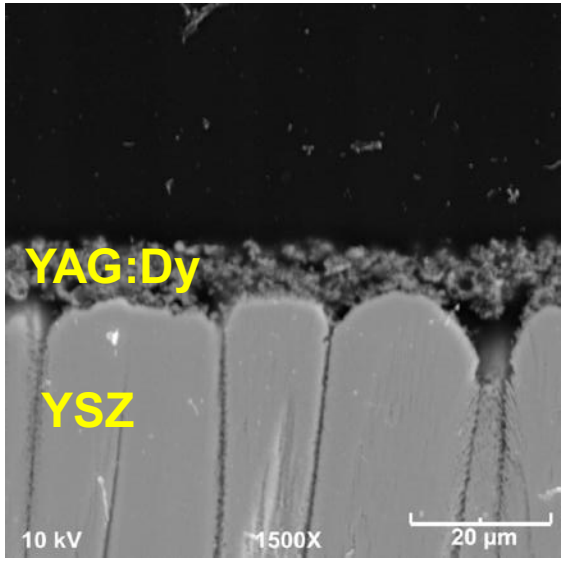
- YAP:Dy displays less single exponential decay & exhibits thermal quenching at substantially lower temperatures than the desired YAG:Dy coating.
- YAP:Dy not a suitable replacement for YAG:Dy for performing temperature measurements at 1300ºC.
- Producing YAG:Dy coatings by EB-PVD is challenging. Will require optimized multiple ingot evaporation.

SPPS YAG:Dy

SPPS at U. of Connecticut



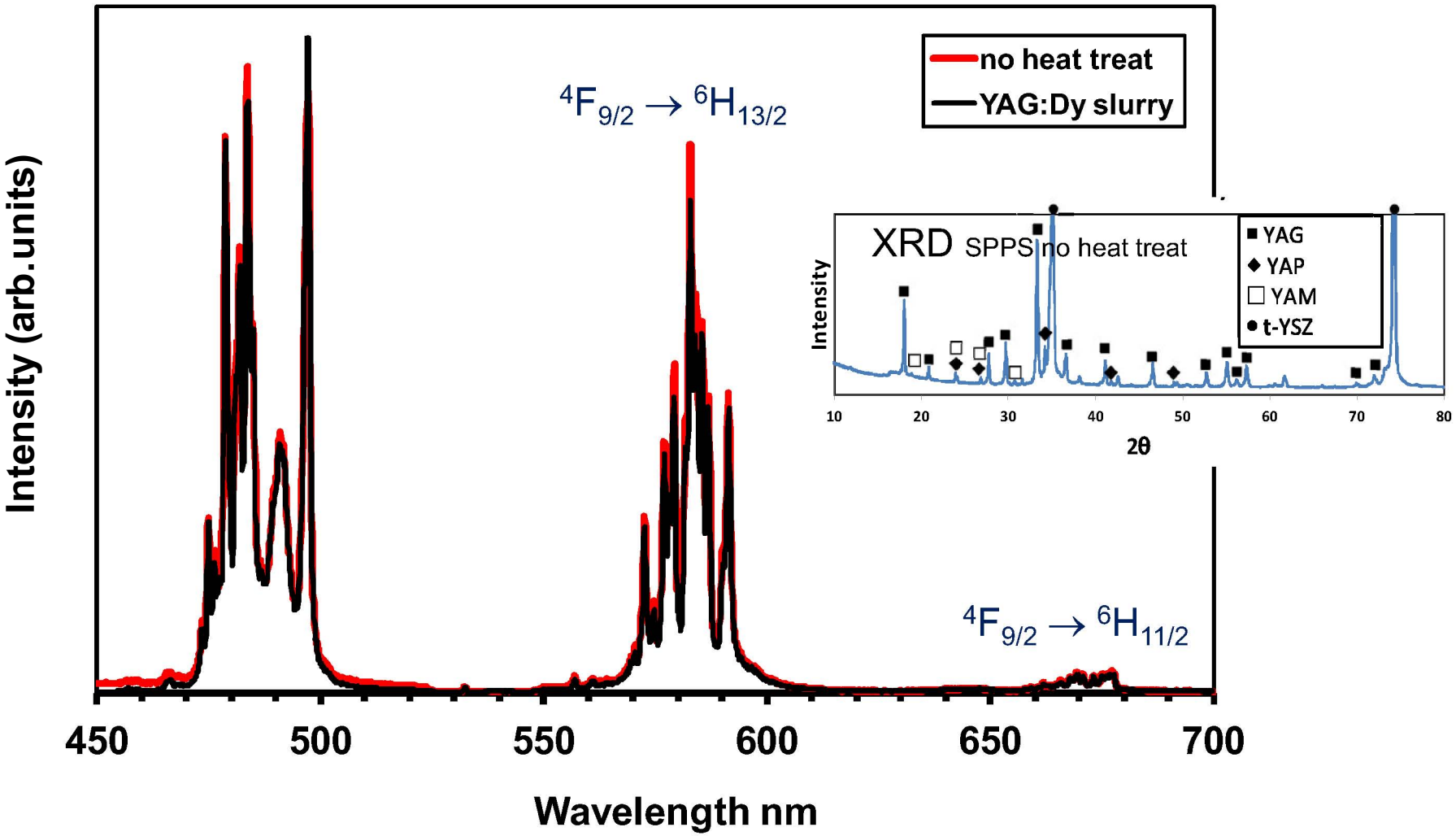




Effect of Heat Treatment on SPPS YAG:Dy

Time-Averaged Luminescence Emission

$^4F_{9/2} \rightarrow {}^6H_{15/2}$ Excitation at 355 nm



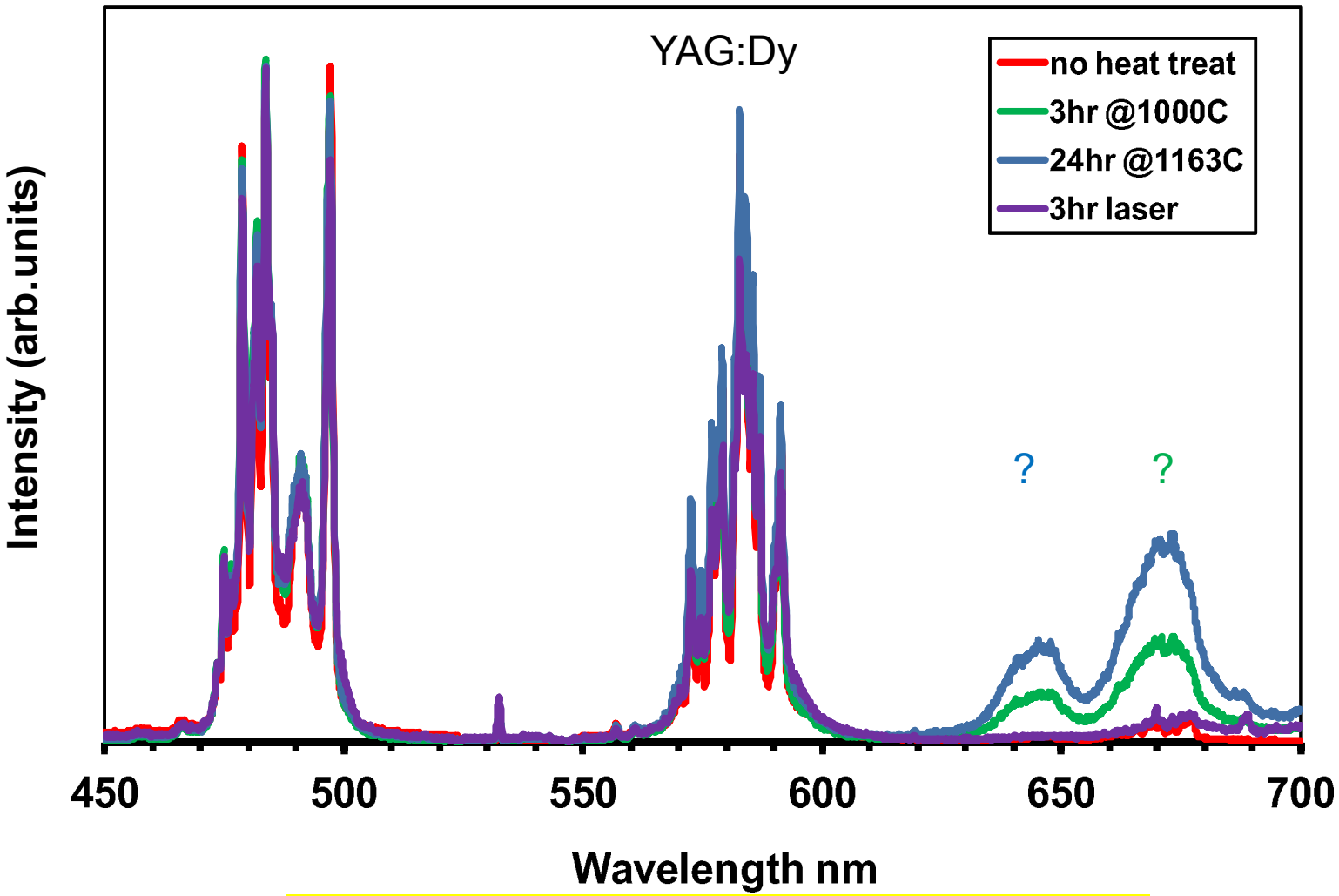
SPPS YAG:Dy coating exhibits desired YAG:Dy emission spectrum.

Effect of Heat Treatment on SPPS YAG:Dy

Time-Averaged Luminescence Emission

Excitation at 355 nm

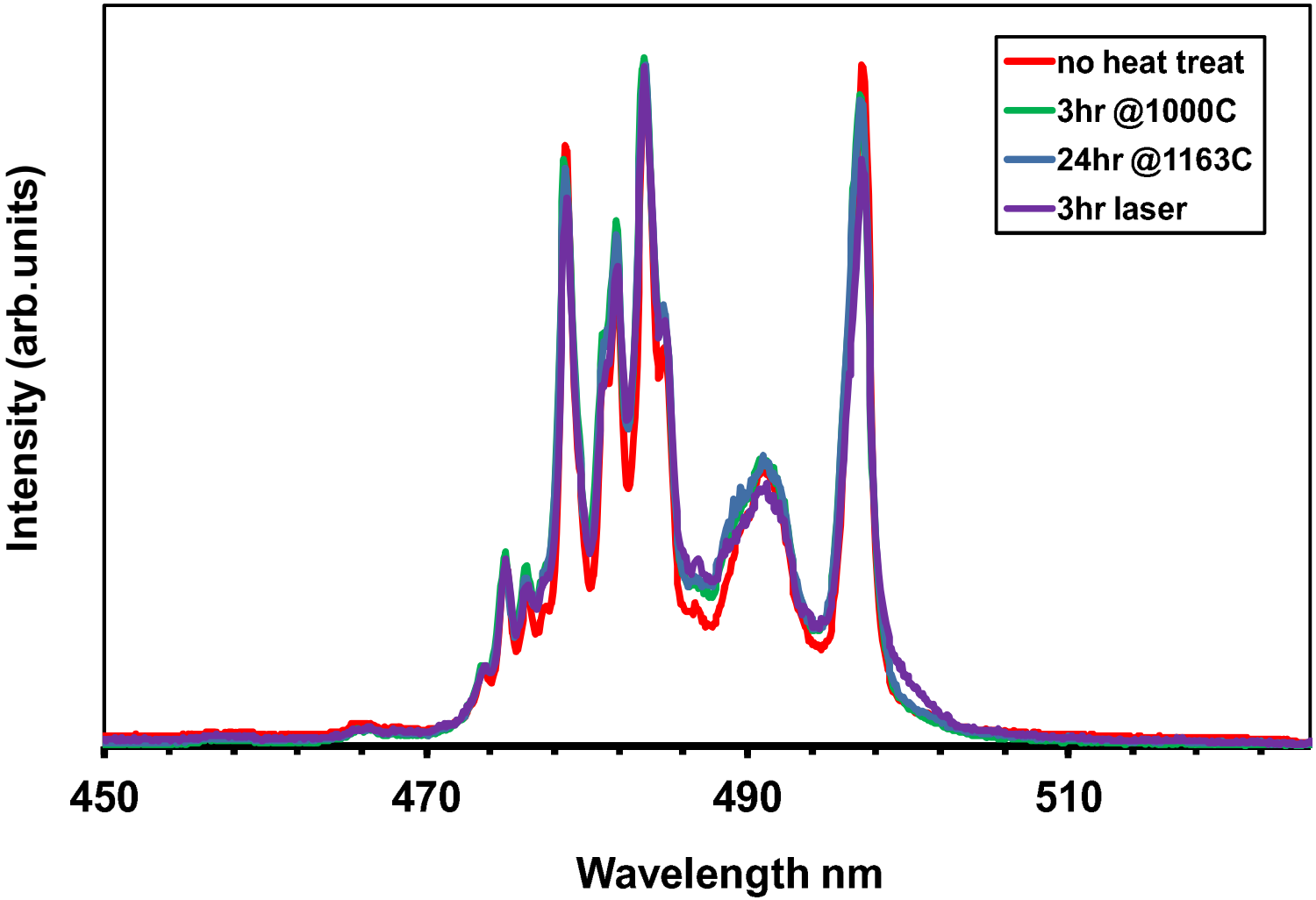
YAG:Dy



SPPS YAG:Dy survives high temperature exposures!

Effect of Heat Treatment on SPPS YAG:Dy

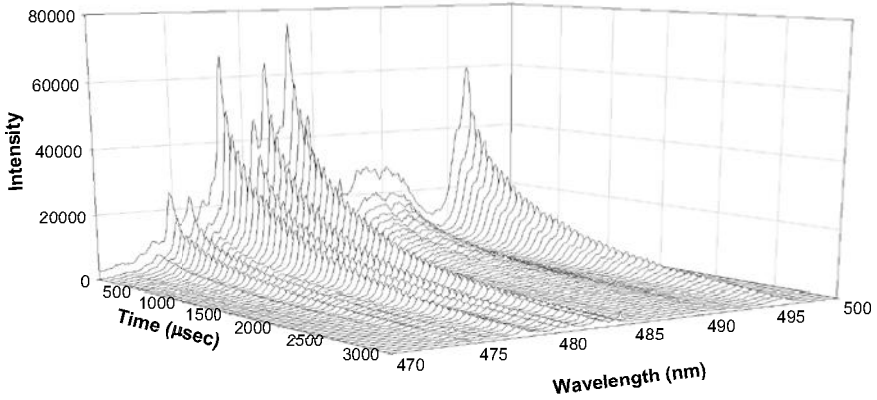
Time-Averaged Luminescence Emission
Excitation at 355 nm



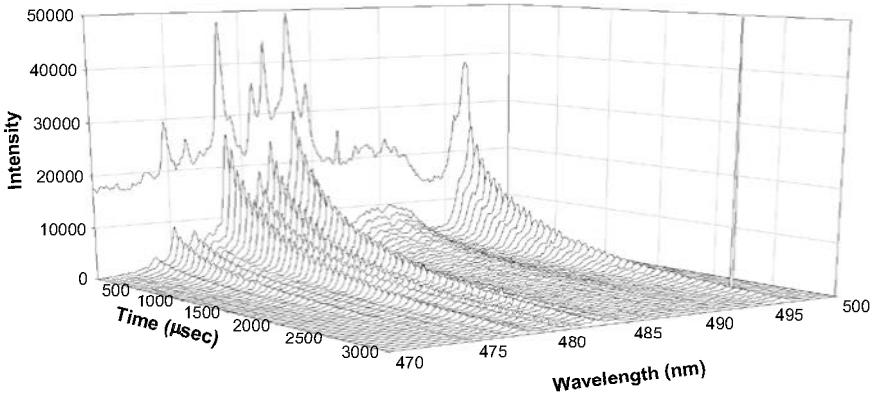
SPPS YAG:Dy resistant to change with high temperature exposure. *Very promising.*

Time-Resolved Luminescence
15ºC

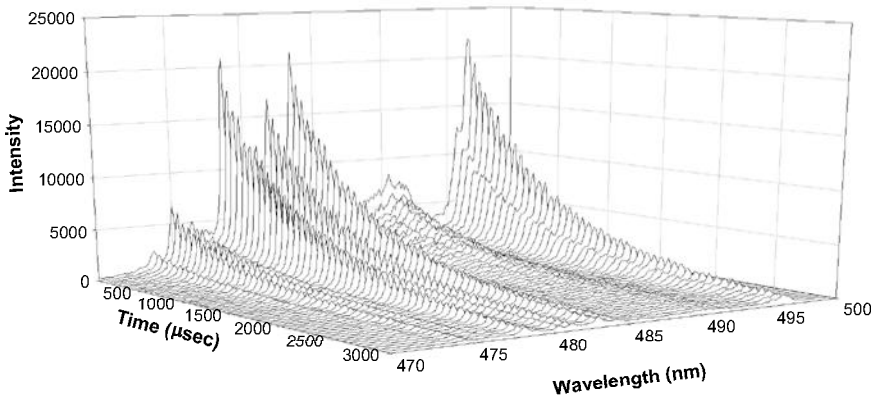
SPPS YAG:Dy no heat treatment

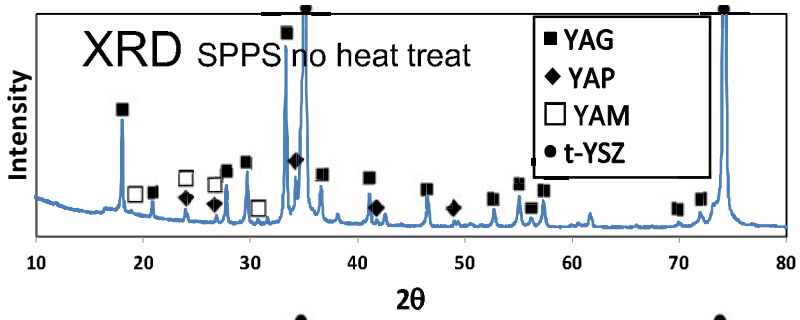


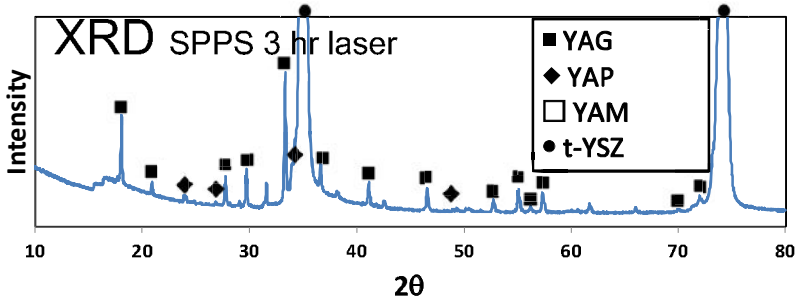
SPPS YAG:Dy 3hr laser Ts=1300ºC



YAG:Dy Powder Standard



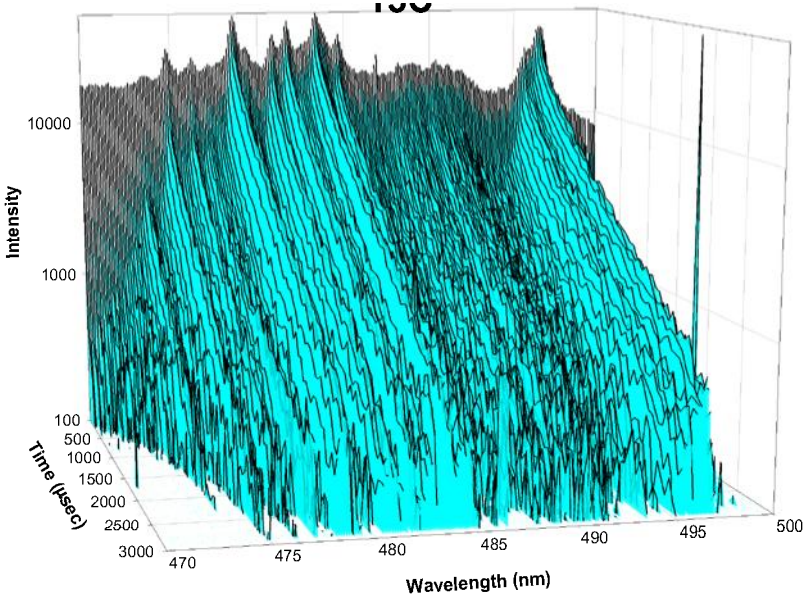




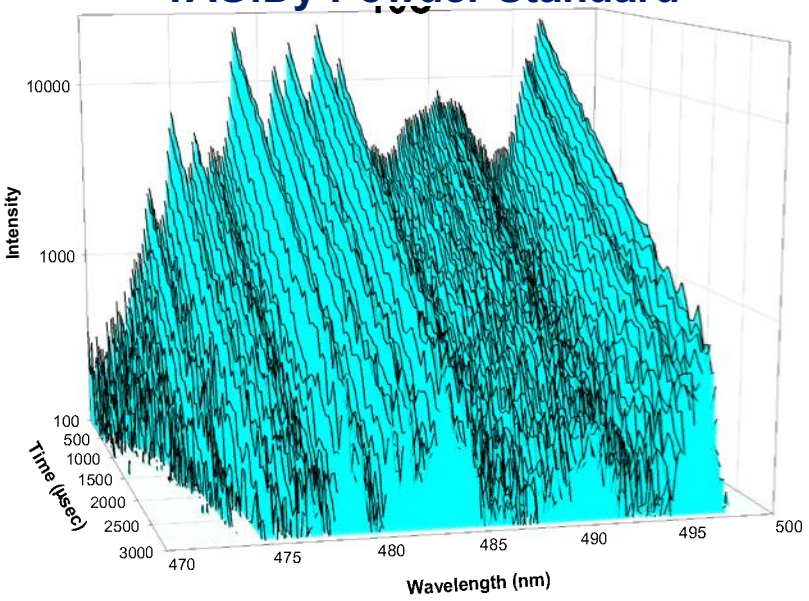
- **After fast initial decay, SPPS YAG:Dy *before & after* heat treatment exhibit emission spectrum + decay identical to that of YAG:Dy powder standard. *Very promising.***
- **Heat treatment reduces minor YAM & YAP content.**

Time-Resolved Luminescence with Logarithmic Intensity Scale 15ºC

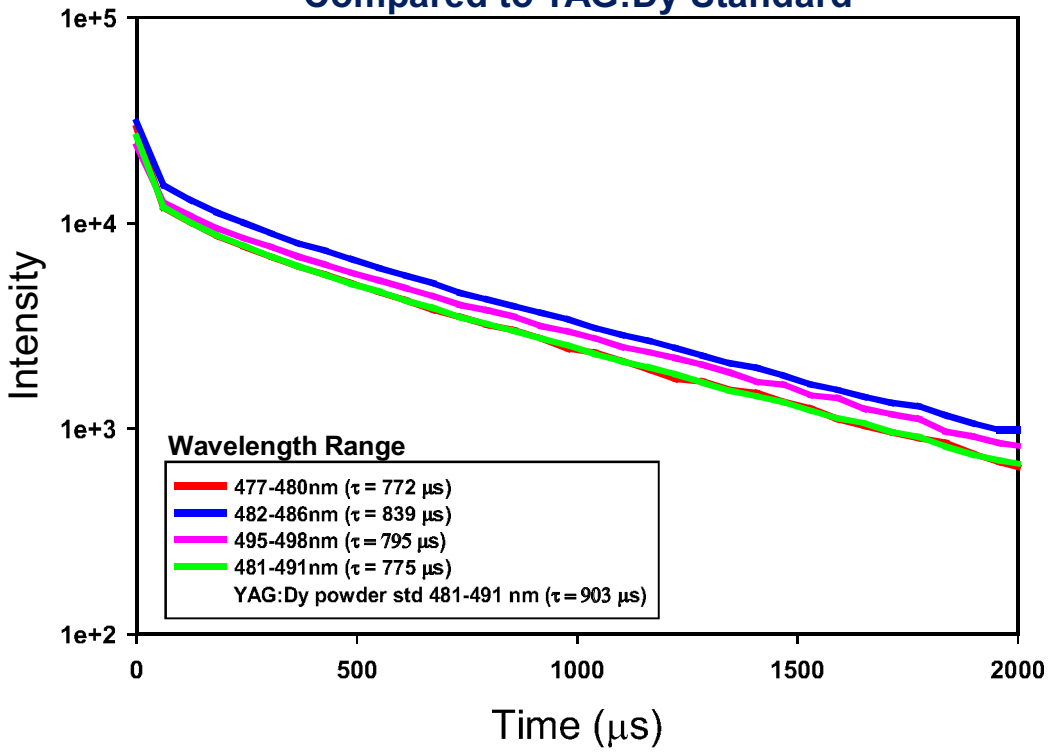
SPPS YAG:Dy 3hr laser Ts=1300ºC



YAG:Dy Powder Standard

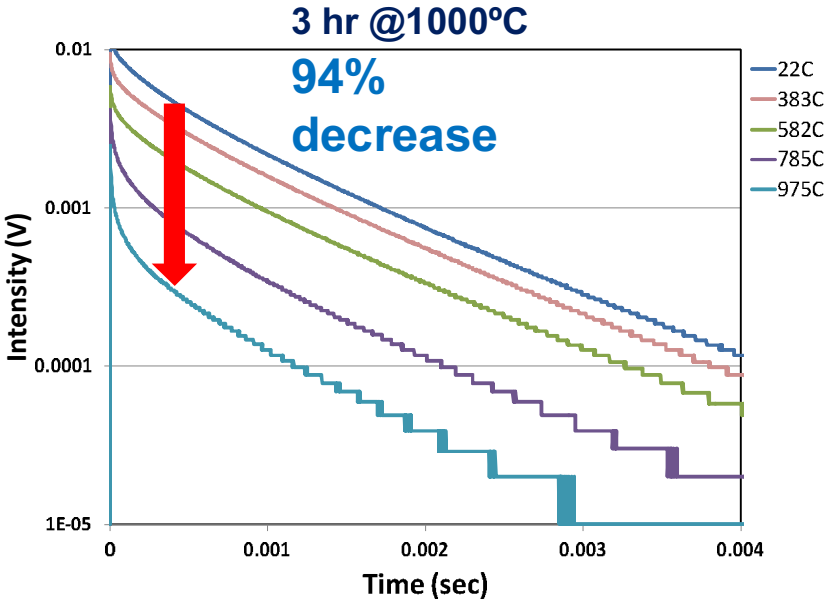


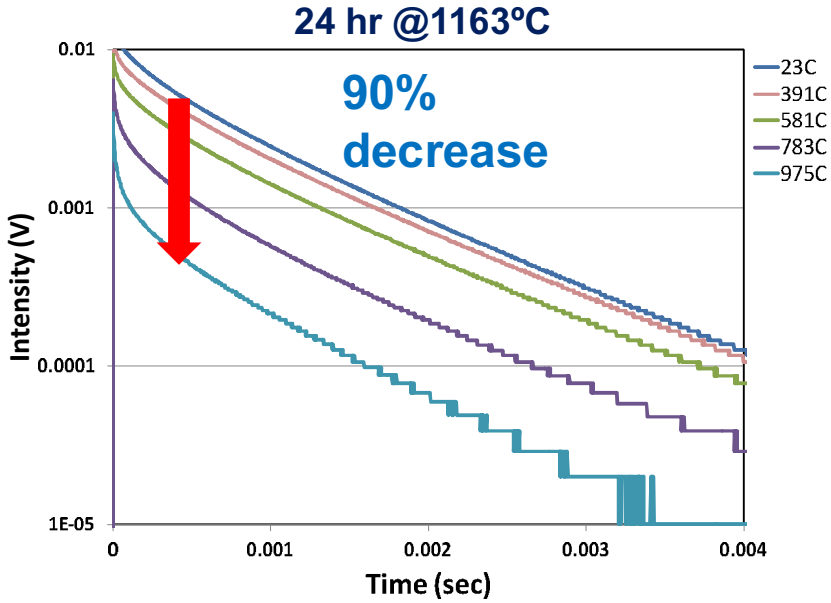
SPPS YAG:Dy
3hr laser Ts = 1300ºC
Luminescence Decay Curves at 15ºC
Compared to YAG:Dy Standard

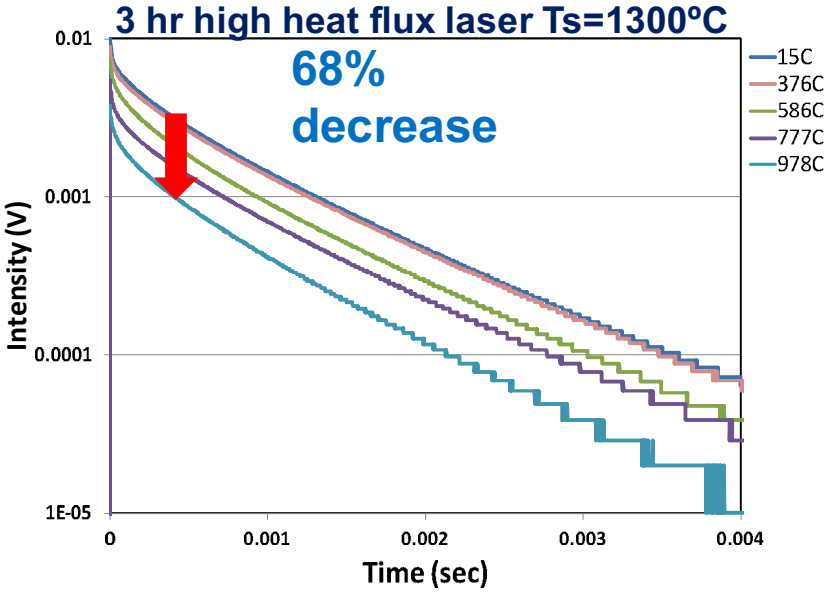


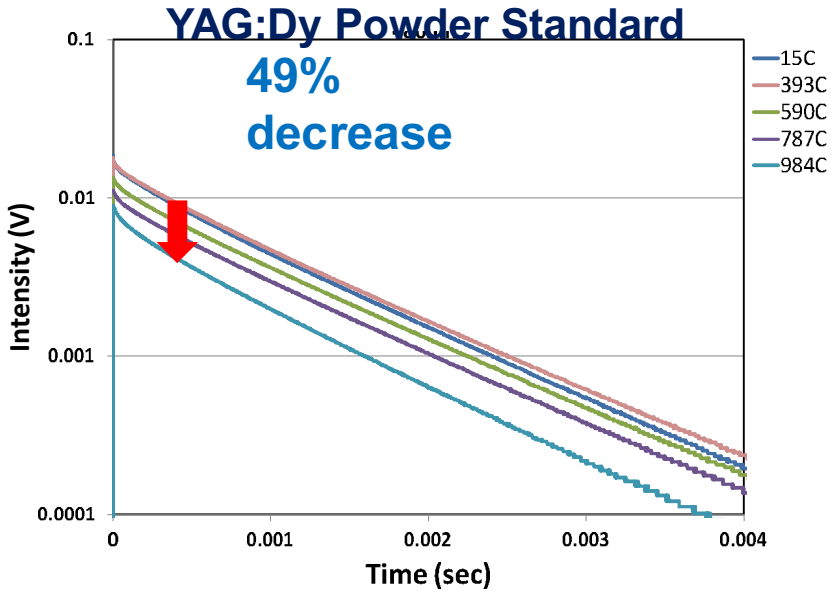
- **Except for initial fast decay, similar to YAG:Dy standard.**
- **Uniform decay rate over full wavelength range.**

Heat Treatments Improve High Temperature Luminescence Intensity for SPPS YAG:Dy





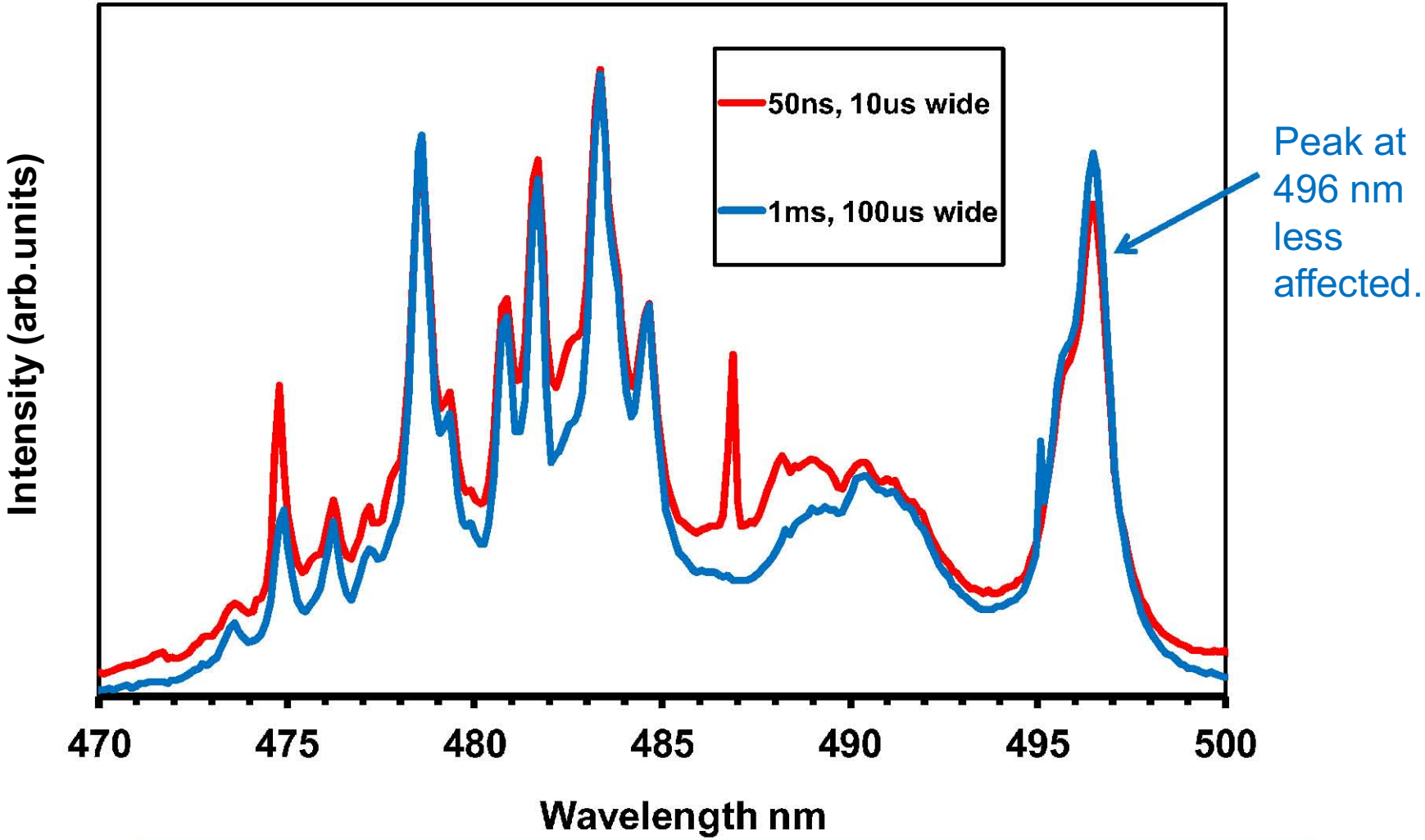




SPPS YAG:Dy coatings benefit from heat treatments or engine run-in.

Faster Decay from YAM:Dy & YAP:Dy Content
SPPS YAG:Dy, no heat treatment

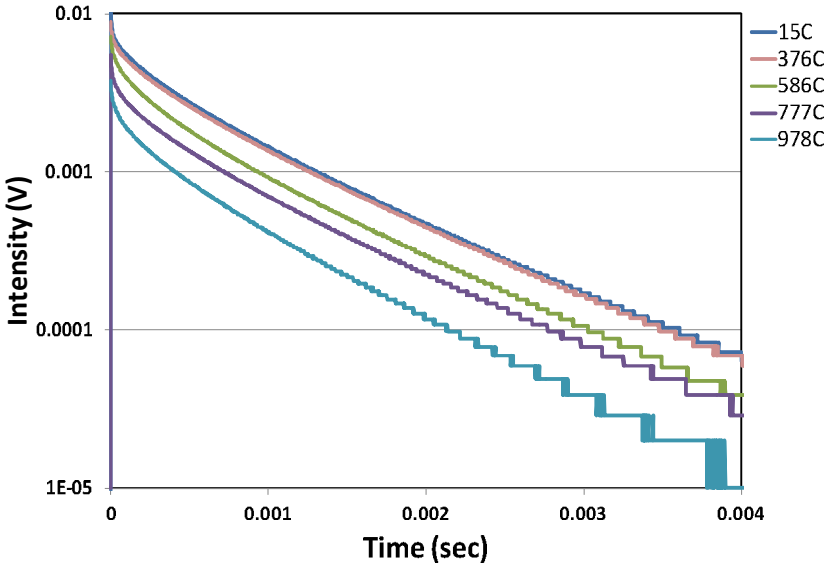
Comparison of Time-Gated Luminescence Emission at Short & Long Delays after Laser Excitation



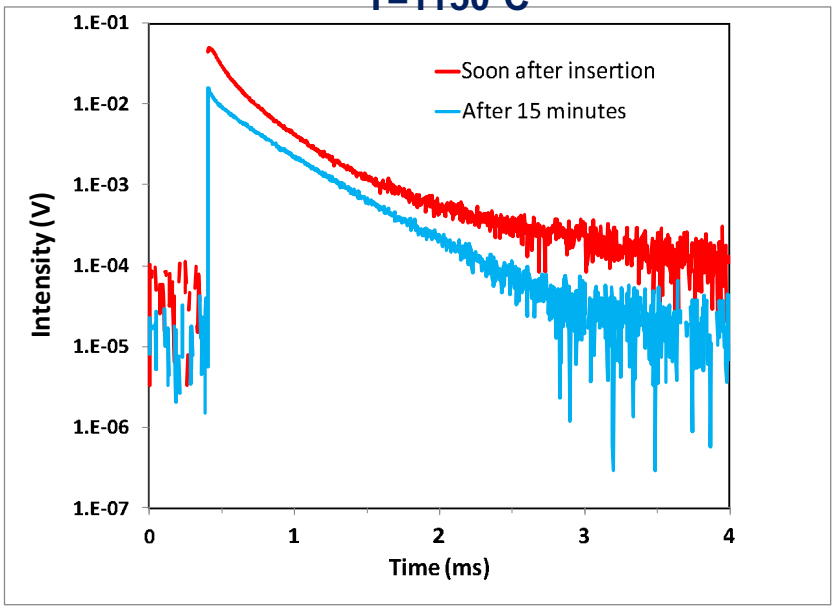
Minor YAM & YAP have disproportionate effect on early stages of decay.
YAM:Dy & YAP:Dy decay faster than YAG:Dy.
Heat treatments should reduce YAM & YAP content.

SPPS YAG:Dy Selected for Near-Term Engine-Testing

SPPS YAG:Dy
after3 hr high heat flux laser Ts=1300ºC



Effect of Exposure to Williams International Combustor Burner Flame T=1150ºC



- SPPS YAG:Dy is suitably robust & stable at turbine engine temperatures.
- Heat treatment or engine run-in is recommended prior to temperature calibration.
  - Reduces loss of high temperature luminescence intensity.
  - Produces more nearly single exponential decay.

Summary

- ZAP Binder-Based Paint Application
  - Great for fast, inexpensive demonstration of feasibility.
  - Unsuitable for high temperature measurements >1000ºC for any duration due to severe reaction between binder & YAG.
- EB-PVD
  - YAG:Dy coating difficult to achieve.
  - Simple oxides are better candidates for EB-PVD because incongruent evaporation from ingot is not an issue.
  - May still be best choice for large scale in-line industrial adoption where optimization effort could be justified.
- SPPS
  - Suitable for stable high temperature measurements.
  - Selected for engine measurements.
  - Heat treatment or engine run-in recommended.

Summary

- Dongming Zhu – High heat flux laser testing
- Joy Buehler – Metallography
- Rick Rogers – X-ray diffraction